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In-Flight Evaluation of Control System Pure Time Delays

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An in-flight investigation of the effect of pure time delays on low L/D space-shuttle-type landing tasks was undertaken. The results indicate that the sensitivity of the pilot ratings to changes in pure time delay in pitch is strongly affected by the task and only slightly affected by changes in control system augmentation mode. Low L/D spot landings from a lateral offset were twice as sensitive to pure time delay as normal low L/D landings. For comparison purposes, formation flying was also investigated and was found to be less sensitive to time delay than the landing tasks.

Nomenclature

AGL	= above ground level
ASL	= above sea level
$\bar{c}$	= mean aerodynamic chord
CAS	= command augmentation system
C^*	$= N_z - (V_{co}/57.3g)q$
C_L	$= L/\bar{q}s$
C_{L_α}	$= \partial C_L/\partial\alpha$
$C_{L_{\delta_e}}$	$= \partial C_L/\partial\delta_e$
C_m	$= M/\bar{q}s\bar{c}$
C_{m_q}	$= \partial C_m/(\partial q\bar{c}/2V)$
C_{m_α}	$= \partial C_m/\partial\alpha$
$C_{m_{\dot\alpha}}$	$= \partial C_m/(\partial\dot\alpha\bar{c}/2V)$
$C_{m_{\delta_e}}$	$= \partial C_m/\partial\delta_e$
DFBW	= digital fly-by-wire
g	= acceleration due to gravity = 32.2 ft/s^2
I	= prefix for improved system
I_y	= pitch inertia, ft-lb-s^2
KIAS	= indicated airspeed, knots
K_q	= pitch rate feedback gain
L	= lift force, lb
M	= pitching moment, ft-lb
N_z	= normal acceleration, g
PIO	= pilot-induced oscillation
PR	= pilot rating
q	= pitch rate, deg/s or rad/s
$\bar{q}$	= dynamic pressure, lb/ft^2
s	= Laplace transform variable
SAS	= stability augmentation system
T_D	= time delay, s
V	= true airspeed, ft/s
V_{co}	= crossover velocity = 324 ft/s
α	= angle of attack, rad
$\dot\alpha$	= angle of attack rate, rad/s
γ	= flight-path angle, deg
Δ	= increment

Introduction

IN the summer of 1977, overcontrol tendencies were observed during the approach and landing flight tests of the space shuttle. Initial assessments indicated that time delays associated with the digital flight control system might be a factor contributing to the control difficulties. References 1-3 provide a comprehensive data base for studying the effect of control system phase lags on the flying qualities of fighter aircraft. However, actual landings were not performed in Refs. 1 and 2, and Ref. 3 had not yet been published. Also, these references were based on analog systems; pure time delays such as those generated by a digital control system had never been evaluated in flight. Consequently, a flight test program was conducted in the spring of 1978 on the Dryden Flight Research Center F-8 digital fly-by-wire airplane to verify the validity of existing data when applied to digital flight control systems and to provide insight into the shuttle approach and landing test experience.

Because of the software flexibility of the F-8 DFBW airplane, transport delay (pure time delay) could be easily varied over a wide range. Transport delay in both pitch and roll were evaluated (roll results are not discussed in this paper). Three basic longitudinal control systems were flown with various amounts of transport delay: an unaugmented system, a pitch damper system, and a command augmentation system. The primary task was a landing approach at idle power which simulates low L/D approaches typical of a space shuttle. However, since contemporary experience, particularly that of Ref. 3, indicated that the results could be very sensitive to pilot workloading, a variety of approaches and landing tasks as well as formation flying were utilized in the program.

Description of Aircraft and Flight Control System

The F-8 digital fly-by-wire aircraft (F-8 DFBW) is a modified F-8C single-engine, single-place Navy fighter (Fig. 1). The aircraft has a two-position wing for reducing fuselage attitude during landing approach. The F-8C was modified by removing the entire mechanical control system between the stick and rudder pedals and the actuators and replacing it with a digital fly-by-wire control system implemented in on-board digital computers.

The F-8 DFBW aircraft includes several control law functions for use in active control applications that are pilot selectable. In this paper, only three pitch axis modes are pertinent: direct, SAS (stability augmentation system), and CAS (command augmentation system). In the direct mode, no aircraft response feedback loops are used (Fig. 2). The SAS mode uses washed-out pitch rate feedback to improve short period damping (Fig. 3). The CAS mode is illustrated in Fig. 4. This system combines prefiltered stick deflection with a blend of pitch rate and normal acceleration feedback, generally known as C^* feedback. To minimize excessive stick forces during large changes in airspeed, neutral speed stability is provided by an effective forward loop integration. This integration is provided by a filtered positive feedback loop around the secondary actuators.

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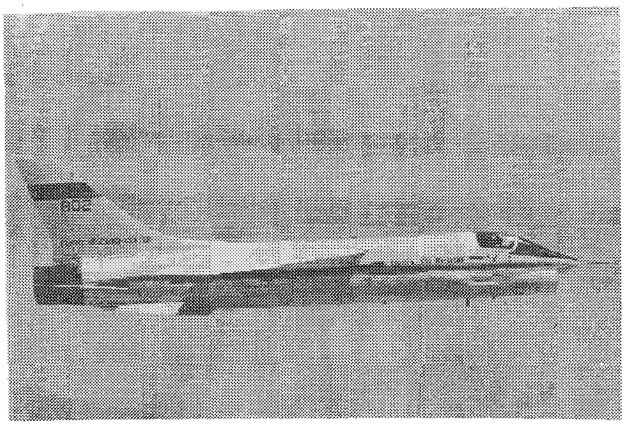

Fig. 1 **F-8 DFBW aircraft.**

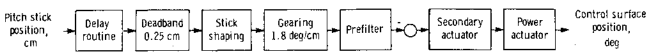

Fig. 2 **Pitch direct mode.**

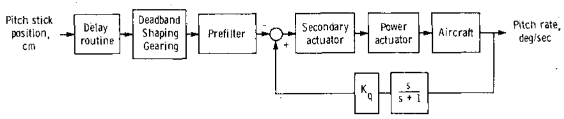

Fig. 3 **Pitch SAS mode.**

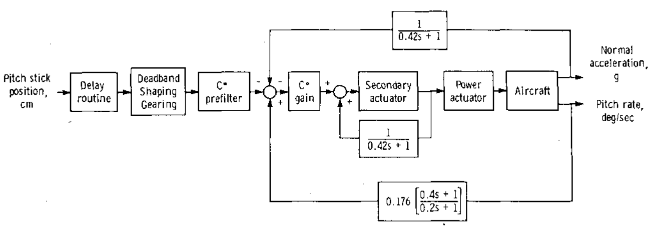

Fig. 4 **Pitch CAS mode.**

Although the basic CAS system was not optimized for low speed flight, it was evaluated in order to provide a spectrum of control system performance which includes off-design conditions. In the latter phases of the investigation, the CAS was optimized for low speed flight. This is referred to as the improved CAS mode or ICAS. The forward loop gain (C^* gain) was increased by a factor of 1.5 and the linear shaping changed to the parabola used in the direct mode (Table 1). At the same time, the SAS prefilter was changed. This is referred to as improved SAS or ISAS (Table 1).

All filtering and control law computation, illustrated in Figs. 2-4, is done in the digital computer. The digital computation and processing introduces pure time delays (transport delays) into the control system. In addition, higher order effects and nonlinearities in the actuators introduce additional apparent transport delays. A typical value for the inherent effective transport delays in the F-8 DFBW control system is presented in Table 1, along with a summary of aircraft and flight control system characteristics. Detailed descriptions of the aircraft and systems can be found in Ref. 4.

Flight Test Procedures

Four basic tasks were evaluated during the flight program: normal low L/D landings, low L/D spot landings, low L/D spot landings from a lateral offset, and formation flying. The formation flying was done to see if an up-and-away evaluation task could provide insight into the control problems that would occur on an actual landing.

Table 1 Typical aircraft and control system characteristics

Gross weight, lb	20,000
Wing area, ft^2	375
$\bar{c}$, ft	11.8
$\bar{q}$, psf	100-270
I_Y, ft-lb-s^2	87,490
C_{L_α}	3.7/rad
$C_{L_{\delta_e}}$	0.57/rad
C_{m_q}	−6
C_{m_α}	−0.5/rad
$C_{m_{\dot\alpha}}$	−0.42
$C_{m_{\delta_e}}$	−0.8/rad
Inherent time delay (stick to surface), s	0.130
Secondary actuator	$\dfrac{15{,}876}{s^2+176s+15{,}876}$
Power actuator	$12.5/(s+12.5)$
Stick shaping	
CAS	Linear
Direct, SAS, ISAS, ICAS	Output = 0.35 × input + 0.45 × input × |input|
Prefilter:	
Direct, ISAS	$50/(s+50)$
SAS	$12/(s+12)$
K_q	$80/\bar{q}$(max = 0.5 deg/deg/s)
C^* gain:	
CAS	$292/\bar{q}$ (max = 3 deg/s/g)
ICAS	$438/\bar{q}$(max = 3 deg/s/g)
C^* prefilter	$0.31\dfrac{0.54s+1}{0.42s+1}\;\dfrac{s^2+23s+177}{s^2+13.5s+55}$

During the low L/D approaches, the engine was at idle power and the landing gear and wing were down. Approaches were initiated at 260 KIAS, 7000 ft above sea level (4800 ft above ground level), about 6 miles from touchdown point. 260 KIAS was held until 500 ft above ground level. The outer glide slope was approximately 10 deg. Flare was initiated 500 ft above ground level. A glide slope of approximately 1 deg was intercepted about 100 ft above ground level. Aim touchdown speed was 190 KIAS; actual touchdown speeds were between 180 and 210 KIAS. Outer glide slope aim point was about 1 mile from the runway threshold.

All landings were made on a concrete runway 15,000 ft long and 300 ft wide. The evaluation terminated at touchdown, and a go-around initiated. The normal low L/D landings were made from straight-in approaches with no particular aim touchdown point. Owing to the generous proportions of the runway, these were relatively unstressed landings. The low L/D spot landings were made from straight-in approaches, but the pilot was asked to touch down at the 5000-ft marker on the runway. The low L/D spot landings from the lateral offset consisted of an approach lined up with the edge of the runway, followed by an offset maneuver (initiated at 100 ft above ground level, approximately 1 mile to touchdown) to line up with the runway centerline, and a touchdown at the 5000 ft marker. The lateral offset increased the pilot's workload and stress, providing a more demanding landing task. Representative flight profiles for these landings are shown in Fig. 5.

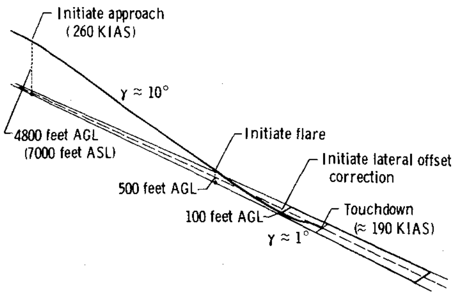

Fig. 5 Low *L/D* landing approach pattern.

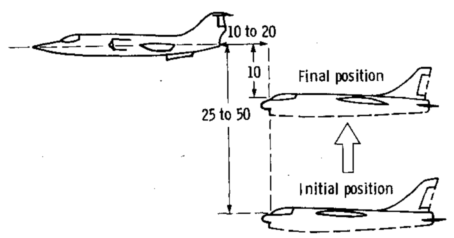

Fig. 6 Formation flying task. Dimensions are in feet.

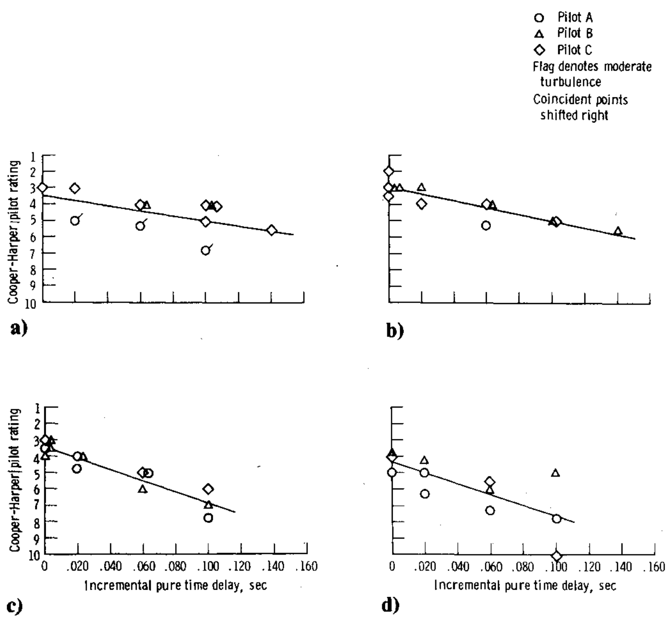

Fig. 7 Variation of pilot rating with incremental pure time delay. a) Low *L/D* normal landing task; pitch SAS mode. b) Low *L/D* spot landing task; pitch SAS mode. c) Low *L/D* offset spot landing task; pitch SAS mode. d) Low *L/D* offset spot landing task; pitch CAS mode.

The formation flying task simulated an aerial refueling positioning. The aircraft was initially stabilized 25-50 ft below another aircraft at various horizontal distances—100 ft the largest, 10-20 ft the closest. Abrupt pitch inputs positioned the F-8 approximately 10 ft below the "tanker" (Fig. 6).

The digital computer was programmed to provide pilot-selectable incremental time delay values of 20, 60, 100, 140, and 200 ms independently in pitch and roll. These increments were added in the pilot input path ahead of the control system feedback summing junction (Figs. 2-4); consequently, the lags within the closed loop portion of the system were unaffected. In addition to these incremental time delays, the aircraft has an inherent pure time delay between pilot stick input and pitch control surface movement of approximately 0.13 s.

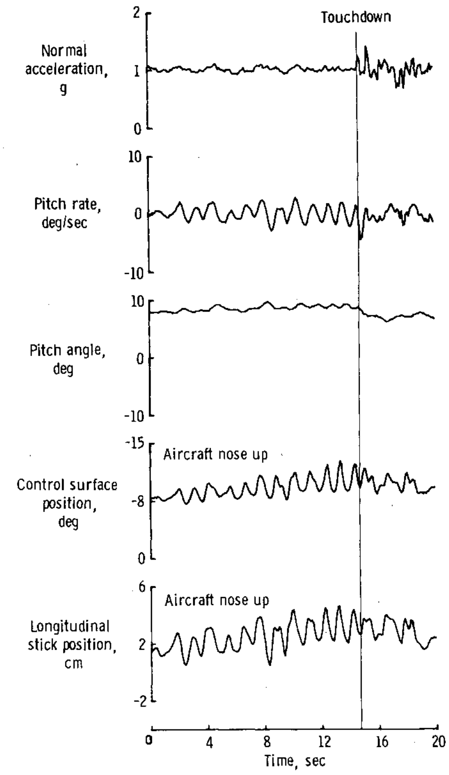

Fig. 8 Time history for normal low *L/D* landing without PIO tendency. SAS mode; 0.060 s incremental time delay; pilot rating 4.

The study consisted of 16 flights and 170 evaluations, with four pilots participating. There was one approach or formation flying task per evaluation. Six flights were primarily pilot check-out and indoctrination in which the pilots familiarized themselves with the various configurations, explored various tasks, and conducted preliminary evaluations. On subsequent flights the pilots formally evaluated the various tasks for different time delays, and provided comments and ratings. The Cooper-Harper rating scale was used.[5]

Because of time and equipment constraints, the pilot was aware of the configuration he was selecting. Also, in most cases, configurations were evaluated in order, starting with zero time delay and increasing to maximum. This introduced the possibility of reduced pilot objectivity. However, it is felt that a high degree of objectivity did exist for the following reasons: 1) All pilots were highly experienced test pilots who had displayed a great degree of objectivity and consistency over the years; 2) none of the pilots knew the ratings assigned by other pilots in the program; and 3) configurations were arbitrarily selected for repeat evaluations. This is confirmed by the good agreement in the ratings between the pilots and for repeated configurations with the same pilot.

Most of the evaluations were performed in air with light turbulence or less. Those data where the turbulence was greater than light are identified.

Results of Pilot Rating Trends

Figures 7a-d present pilot rating as a function of incremental time delay for low *L/D* landing tasks. Figures 7a-c contain data for the SAS control system, and Fig. 7d contains data for the CAS control system. The solid lines are a least-squares, straight-line fit to the data. In most cases the scatter in the data is low and the data are well represented by the straight lines.

Figure 7a contains data for normal, relatively unstressed low *L/D* landings. The data for pilots B and C are in close agreement. The pilot A ratings are somewhat poorer (probably owing to turbulence); however, the trend is the same. Figure 7b presents data for low L/D spot landings. Figure 7c presents data for low L/D offset spot landings. It can be seen that for the most demanding task, offset spot landings, the pilot ratings degrade noticeably faster with increasing transport delay than the previous cases (Figs. 7a and 7b).

Figure 7d presents data for low L/D offset spot landings in the CAS mode. Pilot ratings for no incremental time delay are worse than those for the SAS mode. Also, the CAS data have more scatter at 0.10 s than the SAS data. This can be attributed to the fact that all of the CAS data are degraded relative to the SAS results; consequently, the CAS data at 0.10 s transport delay are closer to an uncontrollable situation than the SAS data. It is common that handling qualities experiments produce increased scatter as controllability boundaries are approached. Bearing this in mind, the least-squares, straight-line fit of Fig. 7d is considered to represent the data well, and it can be seen that it has a slope similar to the SAS mode case (Fig. 7c).

For the more demanding landing tasks, such as the offset spot landings and the larger incremental time delays, PIO's did occur, particularly as touchdown was approached. Figure 8 presents a time history for the touchdown phase of a landing without any PIO tendency reported by the pilot. The landing was made in the SAS mode with 0.060 s of incremental pure time delay. Figure 9 shows a time history for an attempted landing with a PIO reported by the pilot. The landing attempt was made in the CAS mode with 0.10 s incremental pure time delay. Since the pilot control activity for the well-controlled landing of Fig. 8 is quite high (particularly close to the ground), the differences between Figs. 8 and 9 are not immediately obvious. However, it can be seen that in Fig. 9 the frequency of the pilot control activity is somewhat lower and there is a tendency for more divergent bobbling in pitch rate and attitude. In this case, the pilot felt he was definitely out of phase with his control inputs, abandoned the landing, and initiated a go-around.

Potential PIO's and increased uncertainty as to aircraft controllability at the higher time delays made it increasingly hazardous to perform actual landings; consequently, formation flying evaluations were used to see if an up-and-away flying task could be used to provide insight into the potential difficulty with actual landings and also to gather data on category A flying tasks.[6]

Figures 10a-d present pilot rating data for the formation flying task. As before, the straight lines are least-squares fits of the data. Because there was no imminent danger of striking the ground, and since the pilot always had the option of backing out of the refueling position, larger incremental transport delays could be utilized—out to 0.20 s.

Figures 10a and 10b present data for the ISAS and CAS modes, respectively. The latter ratings are degraded somewhat as compared with the ISAS mode, but the trend is similar. The ICAS mode results are shown in Fig. 10c. Ratings for this mode are similar to the ISAS mode.

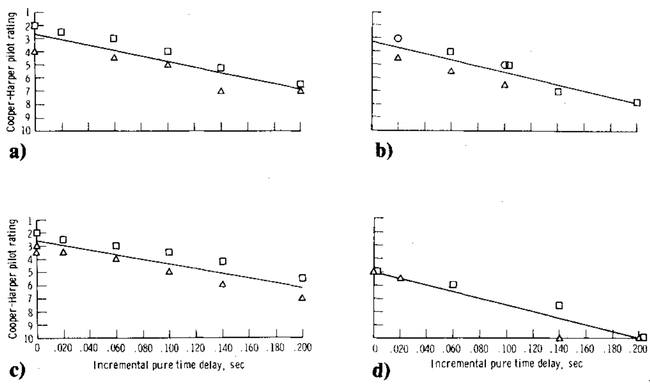

Fig. 10 Variation of pilot rating with incremental pure time delay for the formation flying task (simulated refueling). a) Pitch ISAS mode. b) Pitch CAS mode. c) Pitch ICAS mode. d) Pitch direct mode.

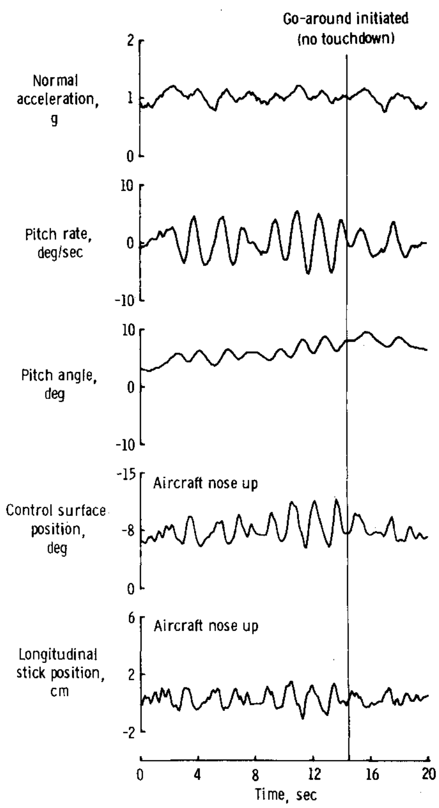

Fig. 9 Time history for offset low L/D spot landing attempt with PIO tendency. CAS mode; 0.10 s incremental time delay; pilot rating 10.

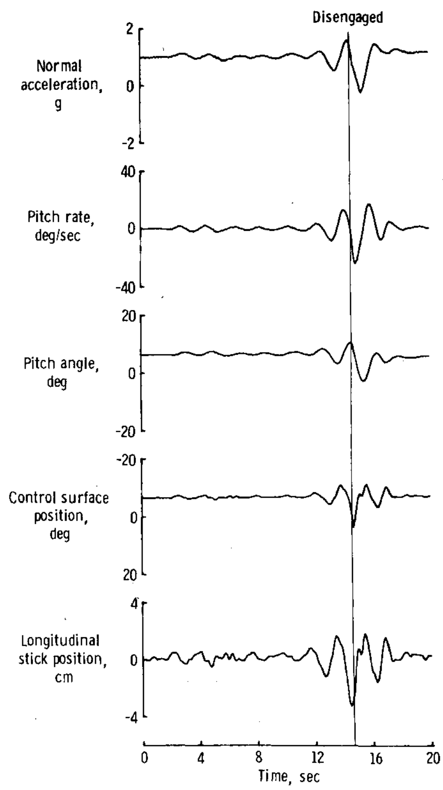

Fig. 11 Flight data for aerial refueling formation flying with PIO. Direct mode; 0.20 s incremental time delay.

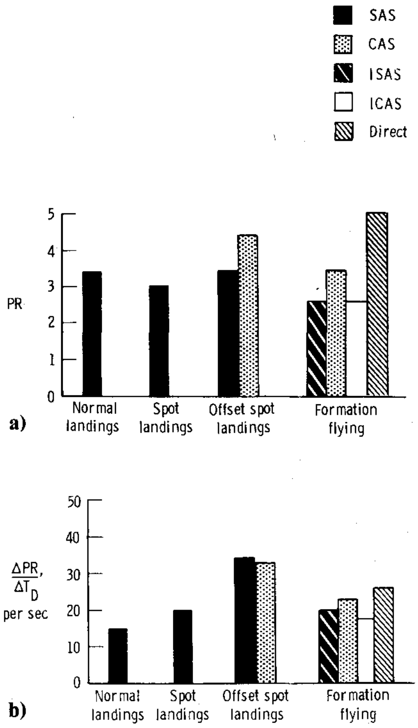

Fig. 12 Summary of the effect of pure time delay on pilot ratings. a) Basic rating. b) Sensitivity to pure time delay.

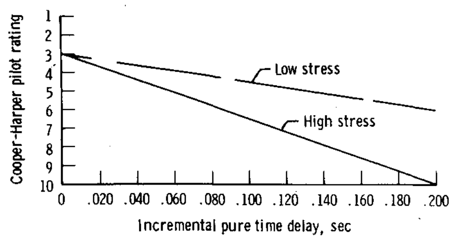

Fig. 13 Pilot rating trends for the low L/D landings.

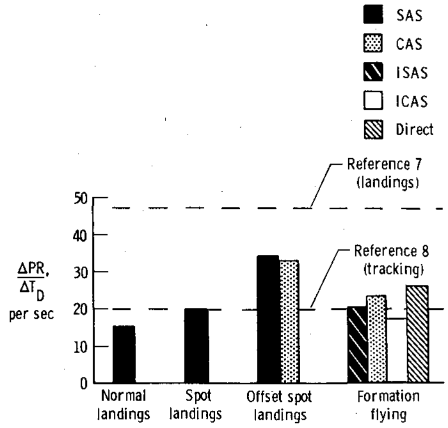

Fig. 14 Sensitivity of pilot rating to pure time delay.

Figure 10d shows data for the pitch direct mode. The ratings are significantly worse than the other modes, and there is some increase in scatter as controllability limits are approached.

Figure 11 presents a time history for a PIO experienced in formation flying. As the pilot tried to stabilize the aircraft precisely in a simulated aerial refueling position, a divergent PIO occurred and the pilot disengaged the time delay.

Figures 12a and 12b summarize the pilot rating results. The basic ratings are the y-intercept (incremental pure time delay = 0) of the least-squares, straight-line fit; the sensitivities are the slopes of the pilot rating with incremental time delay. It can be seen that for the SAS mode, all landings received essentially the same basic rating, 3-3.5, regardless of the landing task. The CAS mode, however, received a basic rating of 4.5 for the offset spot landings, indicating basically inferior flying qualities compared with the SAS mode for this task.

In formation flying, CAS was found to be inferior to ISAS, whereas ICAS was comparable to ISAS. Pitch direct was clearly the worst mode with a basic pilot rating of approximately 5. Overall, the formation flying task received better basic ratings than the landing tasks, indicating that aerial refueling formation flying was not as demanding as actual landings. Formation flying ratings were 0.5-1 pilot rating unit better than landing ratings for SAS and CAS modes.

Figure 12b illustrates the sensitivity of the pilot ratings to changes in transport delay. As task difficulty increased, the change in pilot rating with transport delay increased markedly, whereas the sensitivity to transport delay changed only slightly for the different control system modes. As task difficulty increased from normal landings to spot landings, the sensitivity for the SAS mode increased from approximately 15 to 20, and as difficulty increased from spot landings to offset spot landings, the sensitivity increased from 20 to 35. The results for offset spot landings for the CAS mode were similar. It can be seen then that the sensitivity to transport delay approximately doubled as the task was increased from a relatively unstressed (normal) low L/D landing to a highly stressed (offset spot) low L/D landing. The insidious nature of this phenomenon is illustrated by Fig. 13.

Here the trend lines for the normal landings and offset spot landings for the SAS mode are presented together for comparison. Transport delay can be tolerated for low-stress landings, since the pilot can adapt relatively easily. However, if the pilot is flying with an incremental transport delay of 0.15 s, for example, in a low-stress landing, and suddenly is disturbed by turbulence or an emergency, he may suddenly go from a case that is mildly unsatisfactory to one that is marginally controllable, with potentially catastrophic results.

Hodgkinson and Johnston[7] examined the effects of time delay on longitudinal dynamics during landing for both transport delay and the equivalent delays of continuous systems. The sensitivity of pilot rating to changes in time delay obtained from Ref. 7 (upper dashed line) are compared with the present study in Fig. 14.

The data from Ref. 7 show greater sensitivity to time delay for the more demanding landings than the data from the present study. This difference may not be significant, since it amounts to only a 1.5 pilot rating unit difference for an incremental time delay of 0.1 s. From this point of view, agreement is fairly good. On the other hand, the difference may be due to a difference in task difficulty for the two studies. The Ref. 7 data base utilized conventional landing approaches with simultaneous lateral and longitudinal offsets. The longitudinal offset was 150 ft above the glide slope, and the lateral offset 200 ft from the runway centerline, with corrections initiated approximately 1/2 mile from the intended touchdown point. The offset approaches for this study consisted of low L/D, idle power approaches with a lateral offset of 150 ft with corrections applied approximately 1 mile before touchdown. To a first approximation, the workload imposed by the low L/D landing is probably similar to that produced by the 150-ft offset and a conventional approach. The lateral offset of Ref. 7, however, was more severe and could be expected to make the overall landing task more taxing to the pilot. With this factor in mind, it can be seen that the results of the present study corroborate those of Ref. 7—pilot sensitivity to time delay is most strongly affected by task difficulty, with greater sensitivity expected from more demanding tasks. It should also be noted that Ref. 7 indicates that pilot ratings are insensitive to time delay until a value of 0.12 s is reached. Since the F-8 DFBW aircraft had an inherent pure time delay of 0.13 s, all the data presented herein are above this threshold value.

In Ref. 8, Hodgkinson et al. used regression to analyze pilot rating sensitivity to equivalent time delay for up-and-away tracking and formation tasks of the Neal-Smith data base[2] (lower dashed line in Fig. 14). It is seen that the results of this study are in good agreement with the Ref. 8 results and further corroborate the fact the pilot rating sensitivity is the same for transport delays and equivalent time delays. It is worth noting that category A tasks (tracking, formation, and aerial refueling) are noticeably less sensitive to time delays in pitch than highly stressed landings.

Pilot Comments

Highlights of the pilot comments follow:

Landing

At 8 or 10 ft, the F-8 was pushed over, but there was no immediate response, then it all came in and I started to get out of phase with it.

Got close to the spot and decided to hit it with a last minute correction. Got suckered in and that caused the oscillation. Just couldn't make last minute corrections. That's insidious; you're going along fine until you make a correction.

My strategy was to make very gradual attitude changes and not control rate of descent closely.

The temptation was great to let it go. I had a very nice sink rate. But I felt I should soften it up just a little. Once I did, I was off to the races.

Float time itself is not important, control over the aircraft while close to the ground is.

Low approaches will not raise the pilot's gain to the landing value.

Formation

In the SAS mode, and 0.1 s delay, I could almost PIO. With 0.14 s delay, I experienced a low amplitude PIO. At 0.20 s, I could excite a large amplitude PIO.

In direct mode, and 0.2 s, I couldn't keep the airplane from going into a divergent PIO if I tried to fly a simulated refueling position.

You have the option of reducing gain in formation, in landing you don't. You can allow oscillations to gradually subside in formation, whereas in landing, your gains get higher instead of lower.

Miscellaneous

There is no adequate simulation of the landing task.

Delays that were marginally acceptable for formation proved to be unacceptable for landing. Formation comes close to showing the difficulty, but is not a substitute for landing.

The offset spot landing is a terrific task to bring out all the little problems. Spot landings drove pilot gains up only slightly.

An unsatisfactory or worse flight control system can look benign until taxed near the maximum.

A pilot will always make strong pulsive force inputs when the aircraft does other than what is desired. This was done whenever I recognized a sizeable delay.

Seems it wouldn't be much different from a big airplane if the initial response was slower. It's a little harder to fly than a large airplane; when it comes in, it comes all at once.

Pilots desire some response immediately upon stick input. It doesn't have to be much, but if he doesn't get response, his gains skyrocket.

Air turbulence considerably complicates the landing task by requiring quick restorative inputs.

These comments reinforce and illustrate many of the factors brought out in the previous discussion: The insidious nature of the flying qualities associated with time delays, the sensitivity of the pilot ratings to the tasks, the criticality of control close to the ground, the stress of actual landings, and the influence of turbulence. The comments on the disharmony between the initial time delay and subsequent "snappy" response suggest that large or basically sluggish aircraft may be less sensitive than fighter aircraft to time delays. This possibly warrants further research.

Concluding Remarks

An in-flight investigation of the effect of pure time delays on low L/D space-shuttle-type landing tasks and aerial refueling formation flying was undertaken with the F-8 DFBW aircraft. The results indicate that the sensitivity of the pilot ratings to changes in pure time delay in pitch is most strongly affected by the task, and only slightly affected by changes in control system augmentation mode. These results corroborate contemporary data. Low L/D spot landings from a lateral offset were twice as sensitive to changes in pure time delay than normal low L/D landings and were considerably more sensitive than formation flying.

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